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An improved photonic analog-to-digital conversion scheme using Mach–Zehnder modulators with identical half-wave voltages

Hongxia He, Hao Chi *, Xianbin Yu, Tao Jin, Shilie Zheng, Xiaofeng Jin, Xianmin Zhang

Key Laboratory of Advanced Micro/Nano Electronic Devices & Smart Systems and Applications of Zhejiang Province, College of Information Science & Electronic Engineering, Zhejiang University, Hangzhou, 310027, China

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ABSTRACT

An improved photonic analog-to-digital conversion (ADC) scheme using Mach–Zehnder modulators (MZMs) is proposed and demonstrated. In the approach, all the MZMs have the same electrode length, which eliminates the need of MZMs with very low half-wave voltages as in the scheme using MZM array with geometrically-scaled half-wave voltages. An electric circuit is employed to realize linear combinations of the detected signals (including subtraction and addition). By properly biasing the MZMs and setting the thresholding voltages in the comparators, a digital Gray-code output is obtained. The proposed ADC scheme can effectively improve the bit resolution compared with the previous photonic ADCs based on the phase-shifting technique. Theoretical analysis and proof-of-concept experiments are presented to verify the feasibility of the proposed approach.

1. Introduction

Analog-to-digital converters (ADCs) with high sampling rate and bit resolution are highly demanded in many modern applications, such as wideband radars, advanced instrumentation, high-speed wireless and optical communications. However, limited by the inherent timing jitter and bandwidth bottleneck, the development of electronic ADCs is much slower than that of digital signal processing [1]. Since 1970s, realization of analog-to-digital conversion with photonic technologies has been considered as a potential way to develop high-performance ADCs and a number of approaches to realizing photonic ADCs have been proposed and demonstrated [2–5]. An ADC scheme with optical quantization and coding using optical external modulators was proposed by Taylor in 1970s [5]. In his scheme, the Mach–Zehnder modulators (MZMs) configured in parallel should have geometrically-scaled half-wave voltages to get a digital Gray-code output. For an N-bit ADC system, N MZMs are needed. But when the bit resolution is more than 4, the half-wave voltage of the MZM at the least significant bit (LSB) is too low to fabricate even with current waveguide and photonic integration technology. To avoid this problem, some solutions have been proposed [6–17], which include the approaches that based on cascaded modulators and that based on phase-shifting technique. The technique based on cascaded modulators can realize equivalent half-wave voltage scaling using modulators with identical half-wave voltages at the cost of serial configuration of modulators [6,7]. Stigwall and Galt proposed a free-space optical system to realize quantization and coding by phase-shifting the transfer function of a Mach–Zehnder interferometer [8,9]. Some alternatives to realize phase-shifting technique in all-fiber systems have been proposed, which include the technique using phase modulator and differential interference [10–12] and the approach using MZMs with identical half-wave voltages [13]. The major drawback of the phase-shifting-based approaches lies in that the number of quantization levels in a system with N channels or MZMs is $2N$, but not 2^N as in Taylor's scheme, which means that the realized number of bits in the phase-shifting-based techniques is lower than that of Taylor's scheme with the same number of MZMs or optical channels.

In this paper, we propose a novel photonic ADC scheme using MZMs with identical half-wave voltages but with improved number of bits. Similar to the principle in [13], we properly bias the MZMs to achieve the required phase shifts of the modulation transfer functions. The key difference is that linear combinations of the detected signals (including addition and subtraction) are implemented by an electric circuit, which can equivalently increase the channel number and therefore improves the bit resolution. The operation principle of the approach is presented. Proof-of-concept experiments of ADCs with 3-bit and 4-bit resolution are implemented to verify the principle. More simulation results on the ADC performance are also presented.

* Corresponding author.
E-mail address: chihao@zju.edu.cn (H. Chi).

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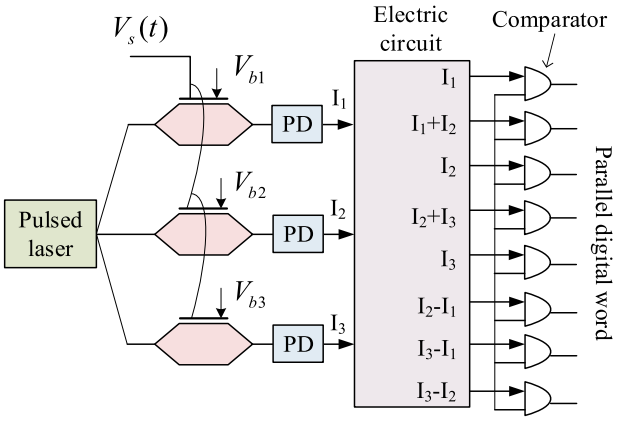

Fig. 1. Schematic diagram of the proposed 4-bit photonic ADC using three MZMs with identical half-wave voltages.

2. Principle

The schematic diagram of the proposed photonic ADC with 4-bit resolution is shown in Fig. 1. The system includes a pulsed laser which acts as sampling source, three MZMs with identical half-wave voltages, three photodetectors (PDs), an electric circuit for implementing linear combinations, and an array of comparators. The repetitive pulses emitted from the pulsed laser are split into three optical channels and in each channel the pulse sequence is modulated by an analog signal to be quantized via an MZM. The bias voltages of the three MZMs are set to be equally spaced to achieve uniform shifts of the transfer functions. After the optical-to-electrical (O/E) conversion performed by the PDs, the detected signals of the three channels are injected into the electric circuit to implement the operations of addition and subtraction. The eight outputs of the circuit, i.e. the linear combinations of the three detected signals, are connected to the comparator array for transforming to "0" or "1" by thresholding.

In our approach, the coding scheme is similar to that in [13] where a digital-Gray code output is obtained by phase-shifting the transfer functions of MZMs. The key difference lies in that in this approach we also use the electric circuit to increase sinusoidal transfer functions with proper phase shifts in addition to properly biasing the MZMs. For simplicity, we take a 4-bit ADC as an example, as shown in Fig. 1. The half-wave voltages of all MZMs are identical, denoted by V_π. In each optical channel, after square-law detection at the PD, the detected photocurrent is given by

$$I_i = \frac{1}{2} I_0 \cdot [1 + \cos(\varphi_s + \varphi_b)] \tag{1}$$

where I_0 is a parameter related to the received optical power and the responsivity of the PD, $\varphi_s = \pi V_s(t)/V_\pi$ is the phase shift induced by the input electrical signal $V_s(t)$, and $\varphi_b = \pi V_b/V_\pi$ is the phase shift induced by the bias voltage V_b. To realize correct coding, the bias phases applied to the MZMs should have a uniform spacing of $\Delta\varphi_b = \pi/4$ and the electric circuit should implement the function (linear combinations) as shown in Fig. 1. To be clear, the output current from the port n of the circuit is denoted by C_n and the first MZM is assumed to be biased at $\varphi_b = 0$. The

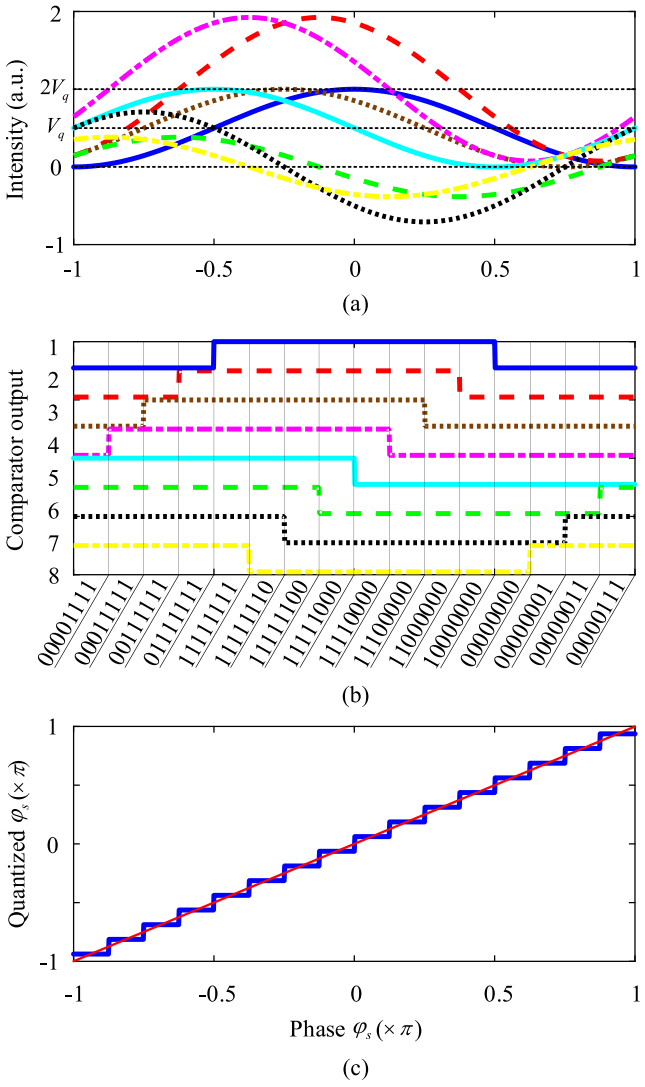

Fig. 2. Coding and quantization principle of the proposed 4-bit photonic ADC. (a) The transfer functions of eight output ports; (b) The codes at the outputs of the comparators; (c) Input phase shift vs. quantized value.

output signals from the eight ports of the circuit are given by Eq. (2).

$$\begin{aligned}
C_1 &= I_1 = \frac{1}{2} I_{in}[1 + \cos(\varphi_s)] \\
C_2 &= I_1 + I_2 = I_{in}[1 + \cos(\tfrac{\pi}{8}) \cdot \cos(\varphi_s + \tfrac{\pi}{8})] \\
C_3 &= I_2 = \frac{1}{2} I_{in}[1 + \cos(\varphi_s + \tfrac{2\pi}{8})] \\
C_4 &= I_2 + I_3 = I_{in}[1 + \cos(\tfrac{\pi}{8}) \cdot \cos(\varphi_s + \tfrac{3\pi}{8})] \\
C_5 &= I_3 = \frac{1}{2} I_{in}[1 + \cos(\varphi_s + \tfrac{4\pi}{8})] \\
C_6 &= I_2 - I_1 = I_{in} \sin(\tfrac{\pi}{8}) \cdot \cos(\varphi_s + \tfrac{5\pi}{8}) \\
C_7 &= I_3 - I_1 = I_{in} \sin(\tfrac{\pi}{4}) \cdot \cos(\varphi_s + \tfrac{6\pi}{8}) \\
C_8 &= I_3 - I_2 = I_{in} \sin(\tfrac{\pi}{8}) \cdot \cos(\varphi_s + \tfrac{7\pi}{8})
\end{aligned} \tag{2}$$

According to Eq. (2), the phase difference between adjacent output ports is equal to $\pi/8$ while the thresholds of comparators are different. At the output ports with expression $C_n = I_i$, the threshold is set as the half of the full scale of corresponding output, denoted by V_q. At the output ports with expression $C_n = I_i + I_j$, the threshold is set as $2V_q$, and that at